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**DETONATION INITIATION OF
HYDROCARBON-AIR MIXTURES IN
A PULSED DETONATION ENGINE**

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14. ABSTRACT Detonation initiation of hydrocarbon-air mixtures is critical to the development of the pulsed detonation engine (PDE). Conventionally, oxygen enrichment (such as a predetonator) or explosives are utilized to initiate detonations in hydrocarbon/air mixtures. While often effective, such approaches have performance and infrastructure issues associated with carrying and utilizing the reactive components. An alternative approach is to accelerate conventional deflagration-to-detonation speeds via deflagration-to-detonation transition (DDT). Analysis of hydrocarbon-air detonability indicates that mixing and stoichiometry are crucial to successful DDT. A conventional Schelkin-type spiral is used to obtain DDT in hydrocarbon-air mixtures with no excess oxidizer. The spiral is observed to increase deflagrative flame speeds (through increased turbulence and flame mixing) and produce 'hot-spots' that are thought to be compression-wave reflections. These hot spots result in micro-explosions that, in turn, then give rise to DDT. Time-of-flight analysis of high-frequency pressure-transducer traces indicate that the wavespeeds typically accelerate to over-driven detonation during DDT before stabilizing at Chapman-Jouget levels as the combustion front propagates down the detonation tube. Results obtained for a variety of fuels indicate that DDT of hydrocarbon-air mixtures is possible in a PDE.						
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Detonation Initiation of Hydrocarbon-Air Mixtures in a Pulsed Detonation Engine

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Detonation initiation of hydrocarbon-air mixtures is critical to the development of the pulsed detonation engine (PDE). Conventionally, oxygen enrichment (such as a predetonator) or explosives are utilized to initiate detonations in hydrocarbon/air mixtures. While often effective, such approaches have performance and infrastructure issues associated with carrying and utilizing the reactive components. An alternative approach is to accelerate conventional deflagration-to-detonation speeds via deflagration-to-detonation transition (DDT). Analysis of hydrocarbon-air detonability indicates that mixing and stoichiometry are crucial to successful DDT. A conventional Schelkin-type spiral is used to obtain DDT in hydrocarbon-air mixtures with no excess oxidizer. The spiral is observed to increase deflagrative flame speeds (through increased turbulence and flame mixing) and produce 'hot-spots' that are thought to be compression-wave reflections. These hot spots result in micro-explosions that, in turn, then give rise to DDT. Time-of-flight analysis of high-frequency pressure-transducer traces indicate that the wavespeeds typically accelerate to over-driven detonation during DDT before stabilizing at Chapman-Jouget levels as the combustion front propagates down the detonation tube. Results obtained for a variety of fuels indicate that DDT of hydrocarbon-air mixtures is possible in a PDE. Successful DDT in air with no oxygen enrichment was achieved with propane, 100 octane low-lead aviation gasoline, kerosene based military jet fuel JP8, and the high energy-density military jet fuel JP10.

I. Introduction

Pulsed detonation engines (PDEs) have experienced renewed interest during the past several decades. To realize potential performance gains of the detonation process,^[1] a practical fuel-air mixture must be successfully detonated. Initiation of detonations remains a technology hurdle for development of practical PDE propulsion systems. As direct initiation of detonations in hydrocarbon-air mixtures requires large ignition energies,^[2] small tube predetonators with oxygen enrichment are often employed.^[3,4] Typically, a smaller volume of fuel-oxygen is utilized as a predetonator in order to initiate detonation of a larger volume of fuel-air. Although capable of reliably initiating detonations, systems of this type require either onboard oxygen tanks or generation systems and are, thus, undesirable for practical propulsion applications.

Alternatively, detonations may be indirectly initiated via acceleration of deflagration to detonation. This deflagration-to-detonation-transition (DDT) process is difficult to achieve in a small volume for complex hydrocarbon fuels in air. The key for performance is to achieve DDT before the deflagrative combustion expands the reactants from the detonation tube. Although direct initiation of detonation is possible, with air as the oxidizer, the magnitude of critical initiation energy for multi-cycle operation is impractical. As shown in **Figure 1**, which is a plot of critical initiation energy versus cell width (λ) for many fuel/oxidizers at stoichiometric and near standard temperature and pressure (STP) conditions, the critical initiation energy for practical hydrocarbon-air mixtures is on the order of 10^5 J,^[2] many orders of magnitude higher than the energy available from a typical spark plug (~100 mJ).

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Consequently, a DDT process is probably required for practical detonation initiation of hydrocarbon-air mixtures without excess oxygen. Hydrocarbon-air DDT has been achieved by Santoro and co-workers who have had some success with ethylene-air mixtures^[5] and by Smirnov et al.^[6] who utilized confinement to promote DDT of gasoline-air.

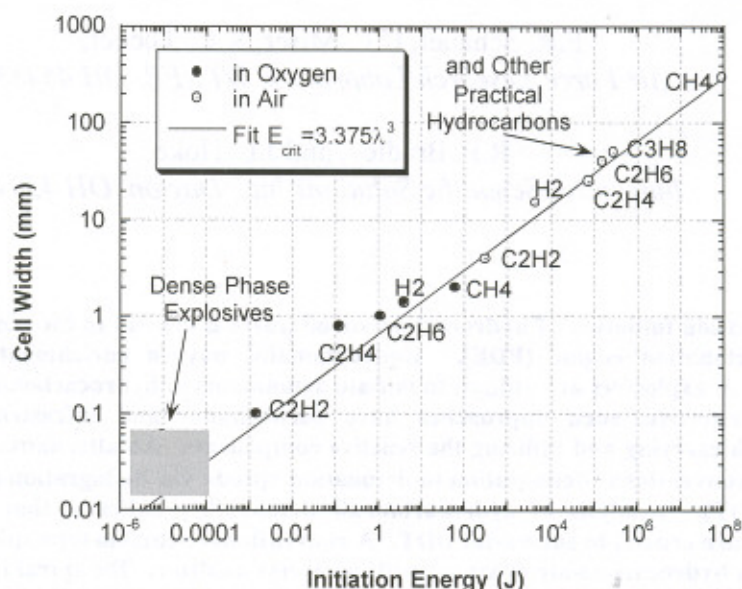


Figure 1. Detonation cell width versus critical initiation energy.^[12]

Researchers at the Pulsed Detonation Research Facility in the Air Force Research Laboratory at Wright-Patterson AFB have had some success in achieving DDT in hydrocarbon-air mixtures within research PDEs. The focus of this paper is detonation initiation of hydrocarbon-air mixtures using a Schelkin-type spiral in a PDE.

II. Theory and Background

Dorofeev et al.^[7] have shown that the minimum DDT distance scales by 7λ . For many practical stoichiometric hydrocarbon fuel-air mixtures near STP, including the fuels discussed herein, the cell width is on the order 50 mm,^[8] very similar to that of propane-air. In theory then, it should be possible to obtain DDT inside the length a typical 1 m long detonation tube with hydrocarbon-air mixtures.

Given that the detonation cell width scales by the total-heat-release induction time,^[9] it follows that any decoupling of heat release will result in increased cell width and a corresponding impact upon initiation requirements. Contributors to the total-heat-release induction time include: chemical-induction and heat-release time, droplet breakup, evaporation, and mixing. Consequently, large droplets and poor mixing will significantly increase cell width and dramatically impact initiation energy or DDT distance.

Figure 2 shows the impact of equivalence ratio upon cell size for several hydrocarbon-air mixtures that have cell sizes similar to those of fuels of interest.^[10] The resultant impact upon critical detonation initiation energy is dramatic as the equivalence ratio departs from stoichiometric, as indicated in Fig. 2.^[11] It is clear that there is a narrow minimum of cell width/initiation energy near stoichiometric. The critical detonation-initiation energy for equivalence ratios that are not near unity is measured in megajoules or kilograms of solid-explosives equivalent. Meyer and co-workers have shown via laser absorption measurements of fuel that significant variations in PDE equivalence ratio can occur in practice.^[12]

Though hydrocarbon-air mixtures should be readily detonable in theory, for the reasons cited above the proper nearly homogeneous mixture with an equivalence ratio near stoichiometric is required; otherwise the detonation initiation requirements can quickly become impractical. In PDE applications, it is extremely difficult to produce an unsteady flow with the proper equivalence ratio. Perhaps it is fortuitous that the difficulty in creating the proper mixture and conditions for detonation serves to reduce the explosive hazard of practical fuel-air mixtures.

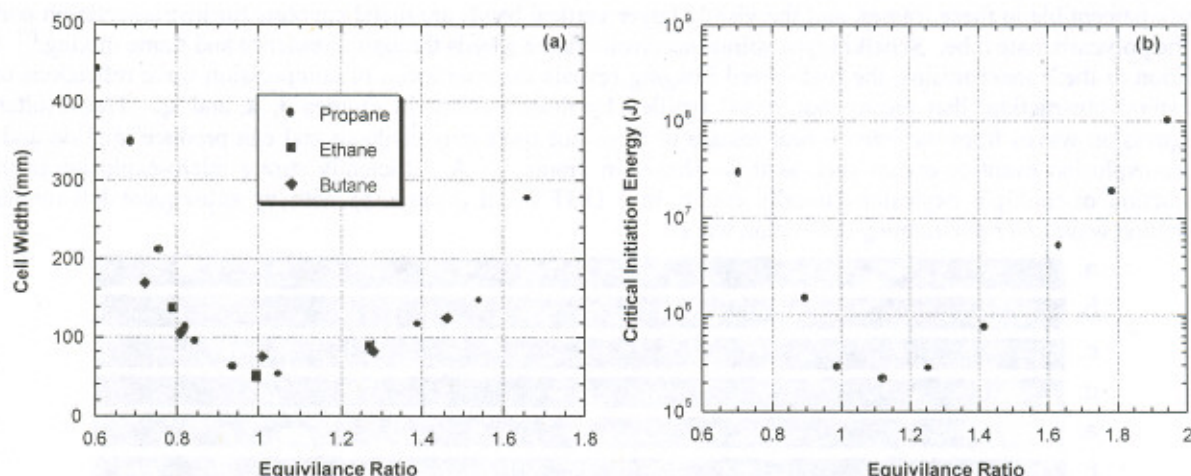


Figure 2. (a) hydrocarbon-air cell width^[10] and (b) propane-air critical detonation-initiation energy^[11] versus equivalence ratio.

III. Experimental Setup and Procedure

Experiments were conducted using the research PDE at the Air Force Research Laboratory's Pulsed Detonation Research Facility. This PDE controls the airflow and cycle timing for up to four detonation tubes using a four-valve-per-cylinder automotive cylinder head for valving. Further details of this engine can be found elsewhere.^[13]

The liquid-fuel injection system developed by Tucker and co-workers was utilized to premix fuel and air prior to the intake manifold.^[14,15] Fuel flow was controlled via selection of fuel-injector-nozzle(s) flow number and fuel pressure. Fuels included: propane, aviation gas (100 octane, low lead, henceforth referred to as 'avgas'), kerosene based USAF jet fuel JP8, and high energy density fuel JP10. Propane and avgas were obtained from local commercial suppliers, and military fuels were obtained from military stocks through the Air Force Research Laboratory's Fuels Branch (AFRL/PRTG).

Weak ignition was achieved in 50.1 mm internal diameter detonation tubes bolted to the cylinder head using an automotive-type spark plug in the stock location. The tubes were mounted to the valve system via an adapter plate which contained instrumentation ports for head pressure and optical sensors. Instrumentation ports were also located along the length of the 1.52 m long tubes. Schelkin-type spirals, 1.22 m long, were located in each of the tubes. The experimental setup and instrumentation are shown schematically in Figure 3.

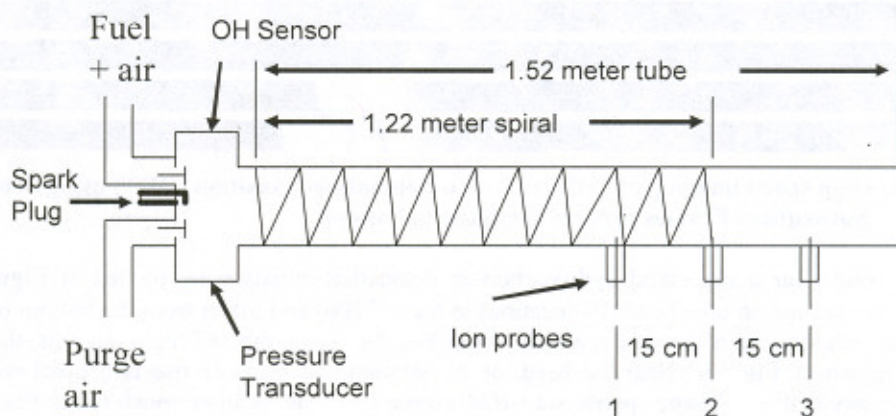


Figure 3. Experimental and instrumentation setup for hydrocarbon-air detonation experiments.

Although stainless-steel detonation tubes were utilized for the majority of experiments, DDT was observed with a polycarbonate detonation tube and fast imaging system, as described by Meyer et al.^[16] Figure 4 shows a typical result, with time evolving in subsequent images from top to bottom in Frames a through z. The spiral is

barely perceptible in these frames, and the visibly larger vertical bands are metal supports for instrumentation ports on the polycarbonate tube. Schelkin-type spirals accelerate flame speeds through turbulence and flame mixing.^[9] In addition to these mechanisms, the high-speed imaging reveals the interaction of compression-wave reflections off the spiral obstruction, that create 'hot spots' typified by those evident in Frames **f**, **k**, and **q**. The resultant compression waves from the intense heat release of these hot spots may coalesce and can produce ignition and a micro-explosion event or events such as those shown in Frame **x**. A sufficiently strong micro-explosion or the interaction of multiple explosions usually results in a DDT event (Frame **y**) with its subsequent left-running retonation wave and right-running detonation wave.

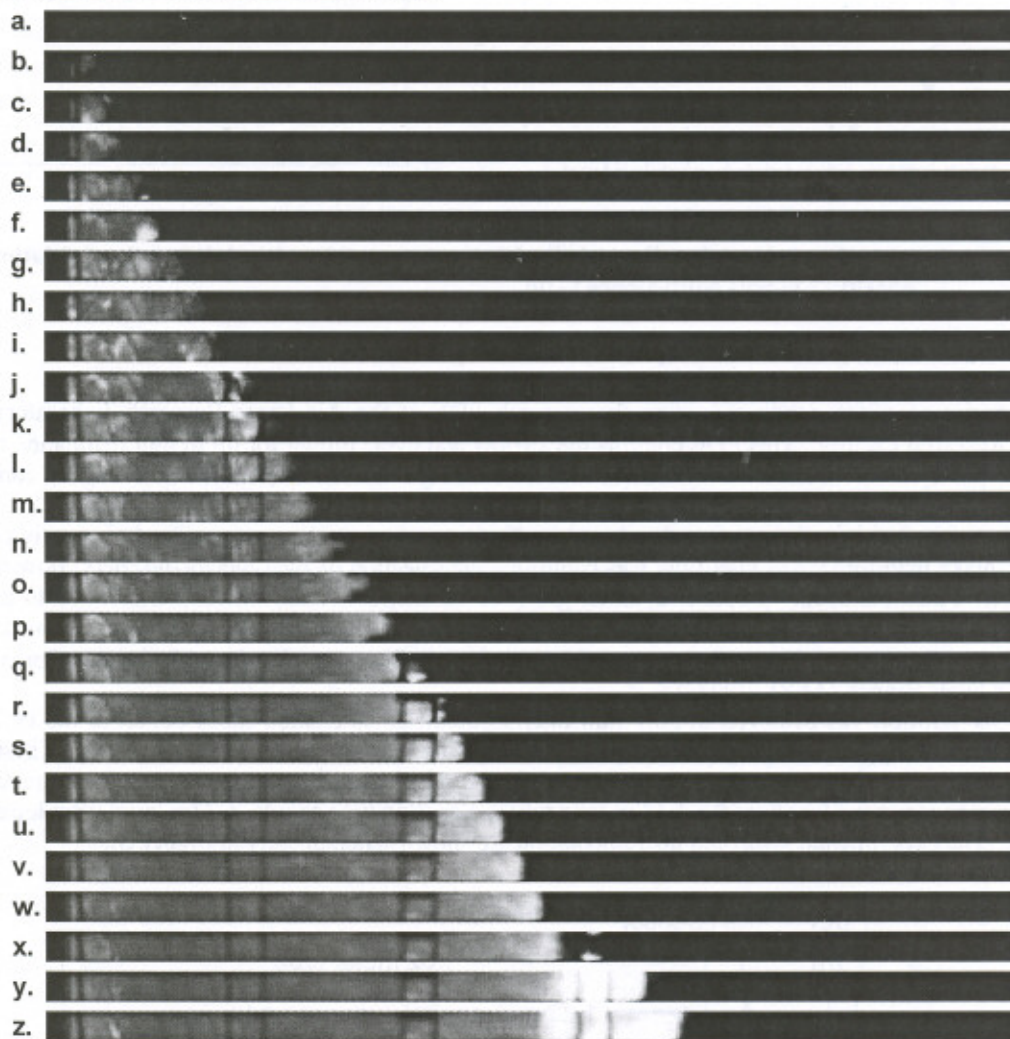


Figure 4. High speed imaging of deflagration-to-detonation-transition (DDT) using Schelkin spiral.
Subsequent Frames proceed from top to bottom.

Typical results for a successful hydrocarbon-air detonation initiation are plotted in **Figure 5**. Pressure traces from near the detonation tube head (P1 location) to the tail (P6) and offset from the bottom of the plot to the top by 30 atm for each location respectively, are shown in **Fig. 5a**. From time-of-flight analysis, the corresponding wavespeeds are shown in **Fig 5b**. Near the head, or P1 location, the pressure rise is gradual with ignition and subsequent flame acceleration. Flame speeds are ~ 1000 m/sec near this location, much lower than the theoretical Chapman-Jouget (CJ) detonation speed. Near the P2 location, DDT occurs, which is evident in the high overpressure of the von-Neuman spike and overdriven detonation wavespeed measurement near this location. The subsequent retonation wave is evident in P1, and the detonation wavespeed decays to the equilibrium value of ~ 1820 m/sec, which is very near the theoretical C-J wavespeed of ~ 1790 m/sec. The reduced pressure spike and

wavespeed near the very end of the tube, at location P6, are indicators of mixture dilution (due to mixing with air at the tube exit) near that location.

Because of the fragile nature, expense, and thermal drift of high-frequency pressure transducers, subsequent wavespeed results were obtained with ion probes^[17] located near the spiral end, as depicted in Fig. 3. It should be noted that ion probes of this type indicate the presence of ions from the combustion front--not the pressure variations detected via pressure transducers. Consequently, ion-probe measurements of wavespeed indicate the combustion wavespeed--not the shock-wavespeed. The combustion-wavespeed measurements are more accurate for evaluating detonation wavespeed since it is possible to have a shock-wavespeed without combustion.

A typical data set is shown in Figure 6(a) for two detonation tubes firing 180 degrees apart at approximately 15 Hz each (30 Hz aggregate). For each data set, results from two detonation tubes (Tubes 1 and 4) were recorded. For each tube, data included the ignition trigger (down transitions of ign), a head pressure trace (not shown in Fig. 6(a) for clarity) and three ion probes (Locations a, b, and c which were 15 cm upstream of the end of the spiral, at the end of the spiral, and 15 cm downstream of the spiral, respectively). As more clearly shown in the plot on the right of Fig. 6, the combustion wave front triggered the ion probes, facilitating wavespeed calculations from time-of-flight analysis. The data shown were from JP10-air at an equivalence ratio of 1.0 and a measured wavespeed of 2230 m/sec and 1823 m/sec, upstream and downstream of the spiral, respectively. The upstream wavespeed is probably overdriven beyond CJ because it is near the DDT location, but the downstream measurement indicates that the detonation is nearing equilibrium. Also shown is tube head pressure, which is significantly lower than the expected P_3 value because of thermal drift of the pressure transducer and possible loss mechanisms described in greater detail by Hoke et al.^[18]

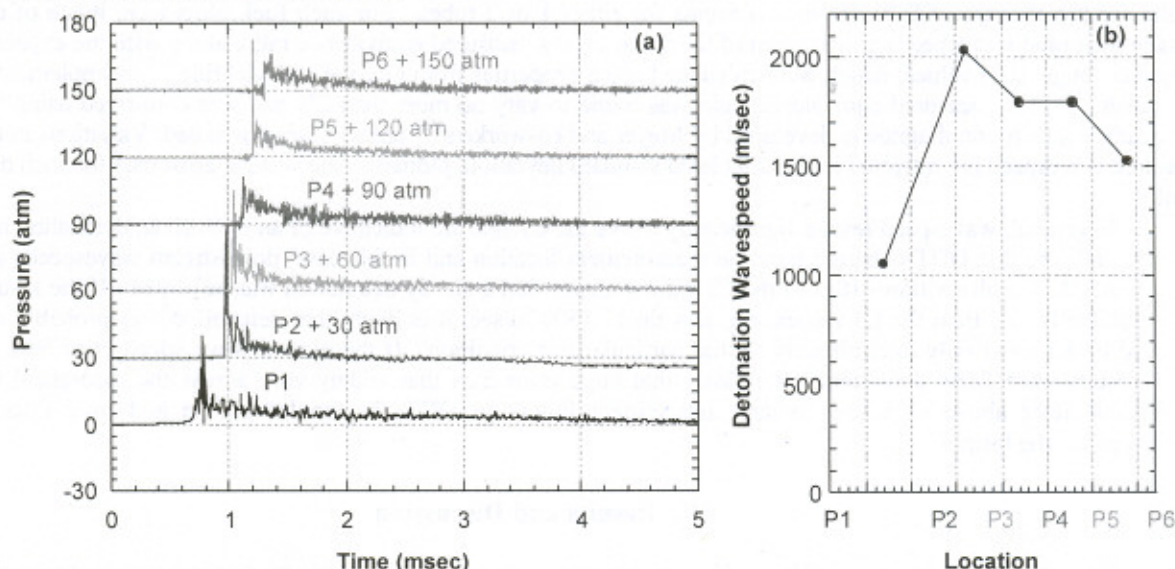


Figure 5. Typical pressure traces (a) for hydrocarbon-air mixtures from near head (P1) to exit (P6) on the tube and bottom to top on the plot, offset for clarity. Time-of-flight analysis provides wavespeed (b).

Due to the sheer volume of data collected (gigabytes), subsequent results contain only the downstream wavespeed measurements. This measurement location provided a convenient means of determining whether detonation occurred while avoiding charge-dilution problems near the end of the tube, as described above with regard to the P6 location measurement of Fig. 5.

Subsequent data were taken using two tubes to minimize equivalence-ratio variations caused by unsteady air flow across the injection system.^[15] Fuel flow, determined via a turbine flow meter and flow calculations across the fuel injectors, is described further elsewhere.^[14,15] Air flow was measured via critical flow nozzles upstream of the unsteady engine,^[13] and both air flow and operating frequency were varied in order to provide the desired equivalence ratio with a full tube fill. Operating frequency was between 10 and 20 Hz per tube. Spark ignition delay was between 6 and 8 msec after inlet valve closure. The inlet air was preheated to $\sim 90^\circ\text{C}$ to avoid puddling of liquid fuel in the intake manifold of this premixed injection system, but performance was found to be fairly insensitive to inlet-air temperature. The fuel heating capability developed by Tucker^[14,15] was not utilized except with JP10 and during a test series with JP8. In both cases the fuel was heated to $\sim 280^\circ\text{C}$. The PDE was run approximately 30-60 sec, allowing the flows to stabilize before data were collected for approximately 1 sec.

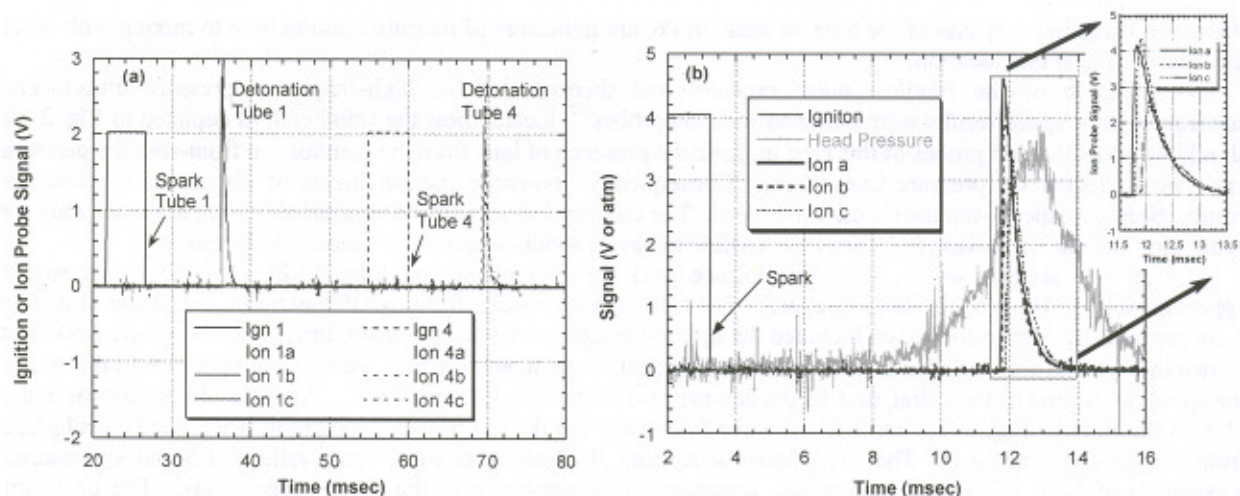


Figure 6. Typical data collected for hydrocarbon-air detonation analysis. Data was collected for multiple tubes (a.) and processed to calculate combustion wavespeeds from time-of-flight past ion-probe signals (b).

Data analysis consisted of post-processing using the routines developed by Parker,^[19] and the following results are the average of 8-20 detonation events for either 1 or 2 tubes. For each fuel, plots were made of the average measured wavespeeds downstream of the spiral versus measured equivalence ratio, along with the expected Chapman-Jouget (CJ) values, which were calculated using properties from Gordon and McBride,^[20] as implemented by Tucker.^[15] The measured equivalence ratio was found to vary no more than 2% and was confirmed using the hydrocarbon absorption diagnostic developed by Meyer and co-workers^[12] unless otherwise noted. Variations in the measured wavespeed are reflected in the calculated standard deviation, plotted as the vertical error bars for each data point.

In general, wavespeed results significantly above the CJ line are indicative of an overdriven detonation and probably indicate that DDT occurred near the measurement location and in this case, downstream wavespeeds are likely near CJ. Results within $\sim 10\%$ of the CJ value indicate that a steady detonation was achieved. If the results are significantly less than the CJ values, e.g. less than ~ 1500 m/sec, it is likely that detonation was probably not achieved or achieved only intermittently at that particular test condition. If the plotted wave speed error bars are small, results were fairly consistent. It follows that large error bars that widely vary across the theoretical CJ wavespeed either above or below indicate intermittent failure to DDT for the latter case and intermittently overdriven for the former.

IV. Results and Discussion

Detonation failed to occur if large droplets were present and/or the fuel-air mixture was not homogenous. In fact, it was extremely difficult to ignite a deflagration if these conditions were present. Ignition characteristics of the fuels tested are not particularly favorable near STP conditions. With the proper fuel injection scheme and mixing, DDT was observed for every fuel tested.

It should be noted, as shown in **Fig. 6(b)**, that the time required from spark to DDT was typically 10 msec and may hinder practical cycle rates. The majority of this time (~ 8 msec) was observed to be the time between spark and establishment of a deflagration flame kernel resulting from the long chemical induction times of hydrocarbon fuels in air at near-ambient conditions.

Measured propane-air wavespeeds versus equivalence ratio are plotted in **Figure 7** and compared to theoretical CJ wavespeeds. Results varied widely with propane-fuel. This is reflected in the data as many points are near 1000 m/sec (choked flame wavespeed). Still propane-air was observed to detonate consistently during some runs with an equivalence ratio of ~ 0.9 . For the wavespeeds above 1500 m/sec near stoichiometric conditions, overdriven upstream wavespeeds (not shown) are indicative that DDT was achieved and the resulting slightly slower wavespeeds probably indicate poor mixing. In general, the ability to initiate a detonation in propane was poorer than with the other fuels reported herein. Factors which may have contributed to the difficulty in detonating include poor mixture control and fuel chemistry.

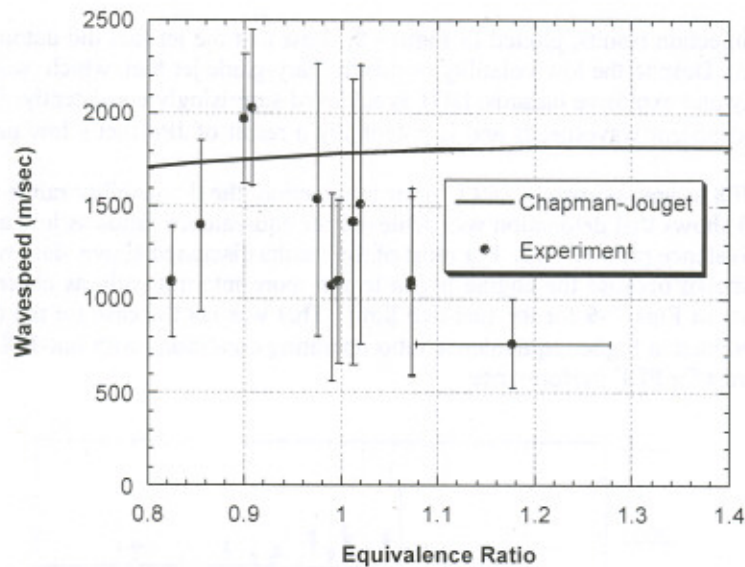


Figure 7. Wavespeed versus equivalence ratio for propane fuel-air.

Propane was the only fuel supplied from a multi-phase storage container. Although data were collected when flow measurements were as stable as possible, fluctuations in fuel flow measurements were indicative of some occurrences of multi-phase flow. Secondly, propane was supplied at lower feed pressures than the other fuels and was thus more susceptible to pressure oscillations in the fuel injection manifold caused by the unsteady inlet air flow. The impact of these effects was estimated and is reflected in the larger error bars shown for the equivalence ratio in Fig. 7 relative to the other fuels in subsequent results.

Propane also has a higher octane number (108) than any other fuel tested in this engine. Tucker observed in the literature and in his own experiments that the octane number significantly impacted DDT events.^[15] Propane, a pure, single-component fuel, may detonate relatively inconsistently due to the lack of small amounts of more detonable species found in multi-component fuels that may contribute to phenomena critical to DDT.

Avgas, with results shown in Figure 8, was observed to detonate consistently for an equivalence ratio ranging from ~0.9 to ~1.3. In general the small error bars and results slightly above the theoretical values indicate that a detonation was consistently established upstream of the measurement location with this fuel. Both the fuel lean and rich results show moderately overdriven wavespeeds—indicative of late (near the measurement location) DDT events.

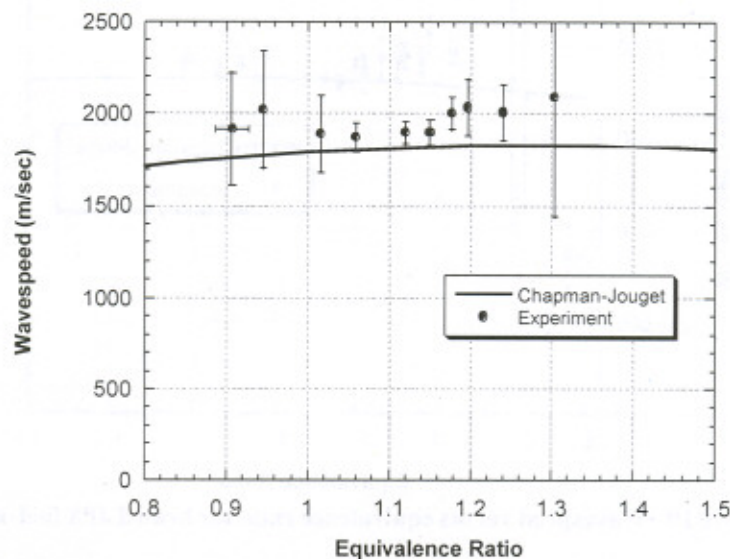


Figure 8 Wavespeed versus equivalence ratio for aviation gasoline fuel-air.

Unheated-JP8 injection results, plotted in **Figure 9**, show that the jet fuel did detonate, but only above an equivalence ratio of 1.05. Despite the low volatility of this military-grade jet fuel, which was specifically designed to minimize flammability and explosive hazards, DDT is achieved surprisingly consistently. This is reflected in the narrow error bars and consistent wavespeeds and is potentially a result of JP8 fuel's low octane rating relative to propane and avgas.

Upon heating JP8 to approximately 280°C prior to injection, the detonability range and repeatability were much better. **Figure 10** shows that detonation was achieved for equivalence ratios as low as 0.9 and in every test data point above an equivalence ratio of 0.95. For most of the results discussed above, data were not taken at higher equivalence ratio than shown because the engine began to run more intermittently as observed by the increasing deviation of the error bars in **Figs. 7-9** for the fuel-rich limit. That was not the case for the data shown in **Fig. 10**; here results were not obtained at higher equivalence ratio operating conditions with hot-JP8 injection because rich operation is of little interest for PDE performance.

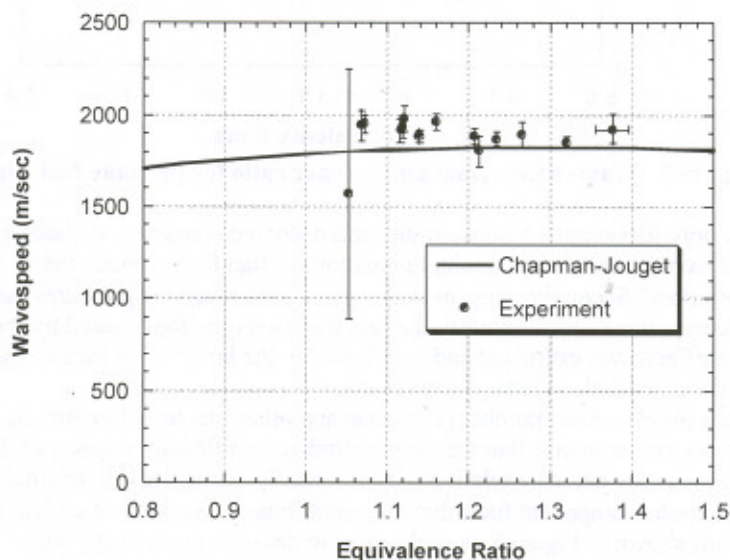


Figure 9. Wavespeed versus equivalence ratio for unheated JP8 fuel-air.

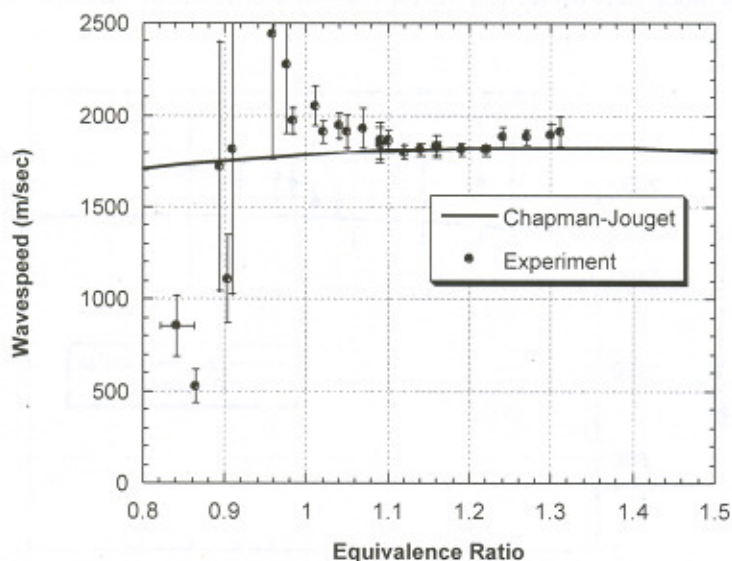


Figure 10. Wavespeed versus equivalence ratio for heated JP8 fuel-air.

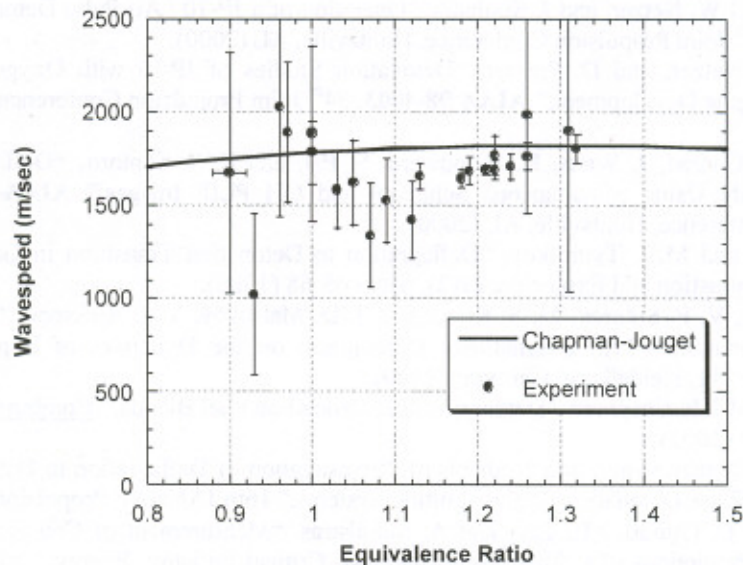


Figure 11. Wavespeed versus equivalence ratio for heated JP10 fuel-air.

Because JP10-air cell sizes are similar to JP8-air, little attention was dedicated to detonation of JP10-air. It was theorized that if JP8-air detonated in the research PDE, then JP10-air ought to detonate in a similar manner. The results in **Figure 11** were obtained to show that it is possible to DDT JP10 in air. Although many of the measured wavespeeds are lower than the theoretical CJ values, most of the results are above 1600 m/sec and well above the choked flame regime. Although these JP10 results represent a much smaller sample set than the other fuels, they indicate that it is possible to obtain DDT with JP10-air for a tested equivalence ratio range of 0.9-1.3. Like propane, JP10 is a signal component fuel, and this may have contributed to the variation in results.

V. Summary and Conclusions

Deflagration to detonation transition (DDT) was achieved within the first 1.22m in a research pulsed detonation engine for a variety of hydrocarbon fuels in air, including: propane, aviation gasoline, JP8, and JP10. The equivalence ratio for successful detonation initiation ranged from ~0.9 to 1.3, which corresponds to a cell width of less than ~100 mm. Thus, these results are consistent with Dorofeev's scaling rules for DDT.^[7] Mixture homogeneity was critical to successful detonation initiation. Failure to produce well mixed reactants with the proper equivalence ratio will likely result in increasing cell size and resultant difficulty in achieving DDT. Fuel heating was helpful when detonating low-volatility fuels. High octane number and single-component fuels had more variability in results.

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